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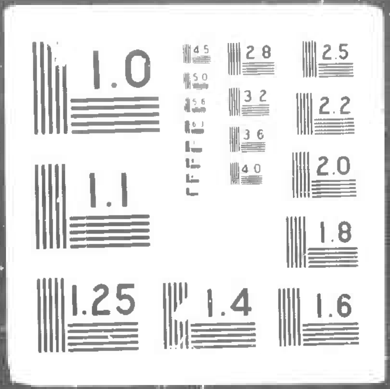

C-BAND PHASED ARRAY CROSSED-FIELD AMPLIFIER DEVELOPMENT

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ABSTRACT

This program effort has two main objectives. The first objective is to demonstrate the feasibility of an RF turn-on, RF turn-off reentrant crossed-field amplifier. The objective of this effort is to obtain RF turn off with a significantly reduced control electrode requirement (e.g., with dc bias) or by eliminating the turn-off electrode completely. To date no significant results have been obtained toward this objective.

The second objective of this program is to increase the power output capability previously demonstrated under Contract AF 30(602)-4082 by a factor of two. During this report period, the first slow wave circuit design for the high power amplifier was completed and cold test work on linear versions was begun. The initial transition match obtained was a 15 db return loss from either port over a bandwidth of 1 GHz. The circuit interaction impedance was measured to be approximately 35 ohms. The thermal properties of the anode (slow wave circuit) were also examined and tested and were found to be capable of sustaining the expected 30 kw of dissipation power.

TABLE OF CONTENTS

LIST OF FIGURES

1.0 INTRODUCTION

This program effort has two main objectives. The first objective (Contract Line Item A001) is to demonstrate the feasibility of an RF turn-on, RF turn-off reentrant crossed-field amplifier to minimize or eliminate modulation requirements. RF turn-on on previous programs at S-F-D laboratories under ARPA Order 136 (Contract numbers AF 30(602)-2533, AF 30(602)-3633, and AF 30(602)-4082) has been demonstrated to be quite reliable and needs very little, if any, further effort. RF turn-off in the present designs is obtained by pulsing a control electrode (which requires a pulse modulator) and has also been demonstrated reliabily on the previous programs. However, the objective of this effort is to obtain RF turn-off with a significantly reduced control electrode requirement (e.g. with dc bias) or by eliminating the turn-off electrode completely. The second objective of this program (Contract Line Item A002) is to increase the power output capability previously demonstrated (on Contract AF 30(602)-4082) by a factor of two. The performance goals are given in Table I.

This development program is a continuation of ARPA sponsored work begun on Contract AF 30(602)-4082. Under that contract, the SFD-237 was developed and operated at a peak power of 1 Mw and an average power of 10 kw. This vehicle incorporated RF turn-on with RF turn-off accomplished through the use of a control electrode. The RF turn-off experiments using this early vehicle were begun on this program at the end of this reporting period, and to date no significant results have been obtained.

During the period covered by this report the first slow wave circuit design for the high power amplifier was completed and cold test work on linear versions of the slow wave circuit was begun. The dispersion curve of the design was adjusted to provide an operating band of 500 MHz from 5.425 GHz to 5.925 GHz. The design of the transition matches from waveguide to the slow wave circuit has been

TABLE I

SPECIFICATIONS FOR EXPERIMENTAL MODEL
FORWARD WAVE CROSSED-FIELD AMPLIFIER

Center frequency	5.675 GHz
Instantaneous bandwidth	500 MHz
Peak power output	2 Mw
Average power output	20 kw
Pulse duration capability	50 μsec
Gain	13 db
Efficiency	40%
Operating voltage	30 kv
Package size (PM focusing)	10" diameter

started. The initial match obtained was a 15 db return loss from either port over a bandwidth in excess of 1 GHz. This match is to be further improved to at least a 20 db return loss with the same bandwidth. The circuit interaction impedance was measured to be approximately 35 ohms. The thermal properties of the anode (slow wave circuit) were also examined and tested. The anode design appears to be capable of sustaining the expected 30 kw of dissipation power with the use of a moderate amount of water as a coolant.

2.0 RF TURN-OFF

In an amplifier utilizing a "cold" secondary emitting cathode, it is possible to apply the operating voltage to the amplifier without drawing current until an RF input pulse is supplied. Upon the application of the RF input pulse, a secondary emission multiplication process causes a rapid buildup of space charge. The process requires RF as well as dc electric fields to occur. Current is drawn by the amplifier and amplification takes place through the normal crossed-field mechanisms. In reentrant stream amplifiers in which electrons circulate from the amplifier output to the input via a drift space, the starting process is extremely rapid and reliable and amplification begins in a matter of a few nanoseconds. At the conclusion of the RF drive pulse, however, the space charge which remains in the amplifier must be cleared from the interaction area or the amplifier via the circulating electrons can become an oscillator or noise generator. The amplifier will not generate spurious outputs prior to the application of the RF pulse because there is no way for electron emission to get started. Low level noise fields cannot energize the few available electrons enough to start the secondary emission buildup. The transition from the driven condition to the self-oscillation or noise generating condition can occur at the end of the RF drive pulse because a space charge cloud exists which can support and amplify the noise fields and in turn cause the secondary emission process to continue.

In the past, the space charge remaining after the removal of the RF pulse has been collected on a third electrode called a control electrode. The control electrode is normally situated on the cathode assembly and during the pulse is kept at approximately cathode potential. At the conclusion of the RF input pulse, a voltage is applied to make the control electrode positive with respect to the cathode to collect the remaining space charge and to prevent recirculation. The ratio of

applied dc voltage to the peak control electrode voltage is generally about 3 to 1, and the control electrode is then said to have a mu of 3.

Figure 1 shows the usual pulsing sequence for a control electrode amplifier. The absence of the control electrode voltage pulse will result in the amplifier operating in essentially a CW noise mode. Figure 2 shows the detected RF envelope of the output with the control voltage pulse delayed so that the amplifier operates for a short time without the drive signal to control it. The fuzzy lower level of RF envelope at the trailing edge is the spurious output. The voltage pulse applied to the control electrode may have any length provided that the voltage remains on until the RF pulse has ended. The energy consumed by the control electrode is quite small compared with the energy in the long pulse output of the amplifier. Further, the energy consumed per pulse depends upon the rate of rise of the control voltage pulse, higher rates of rise leading to lower energy consumption. There is a practical upper limit to the rate of rise of control voltage because of the currents required to charge the stray and interelectrode capacities. Also, as the amplifier pulse width decreases the control electrode consumes proportionately larger amounts of power, thereby limiting its usefulness in pulse burst applications.

One obvious way of removing the space charge would be to insert an electrode which would collect the remaining current and destroy the reentrancy. This device would now be essentially a circular format non-reentrant amplifier. By destroying the reentrancy, the advantage of rapid and reliable starting is reduced and there is a loss in efficiency. The loss in efficiency increases the thermal problems because more of the input power is dissipated in the structure. In order to avoid these limitations, some preliminary experiments were performed on an S-band amplifier to see if the control voltage pulse could be reduced or replaced by a fixed dc voltage which would greatly relax or eliminate the requirements of the control modulator. Indeed,

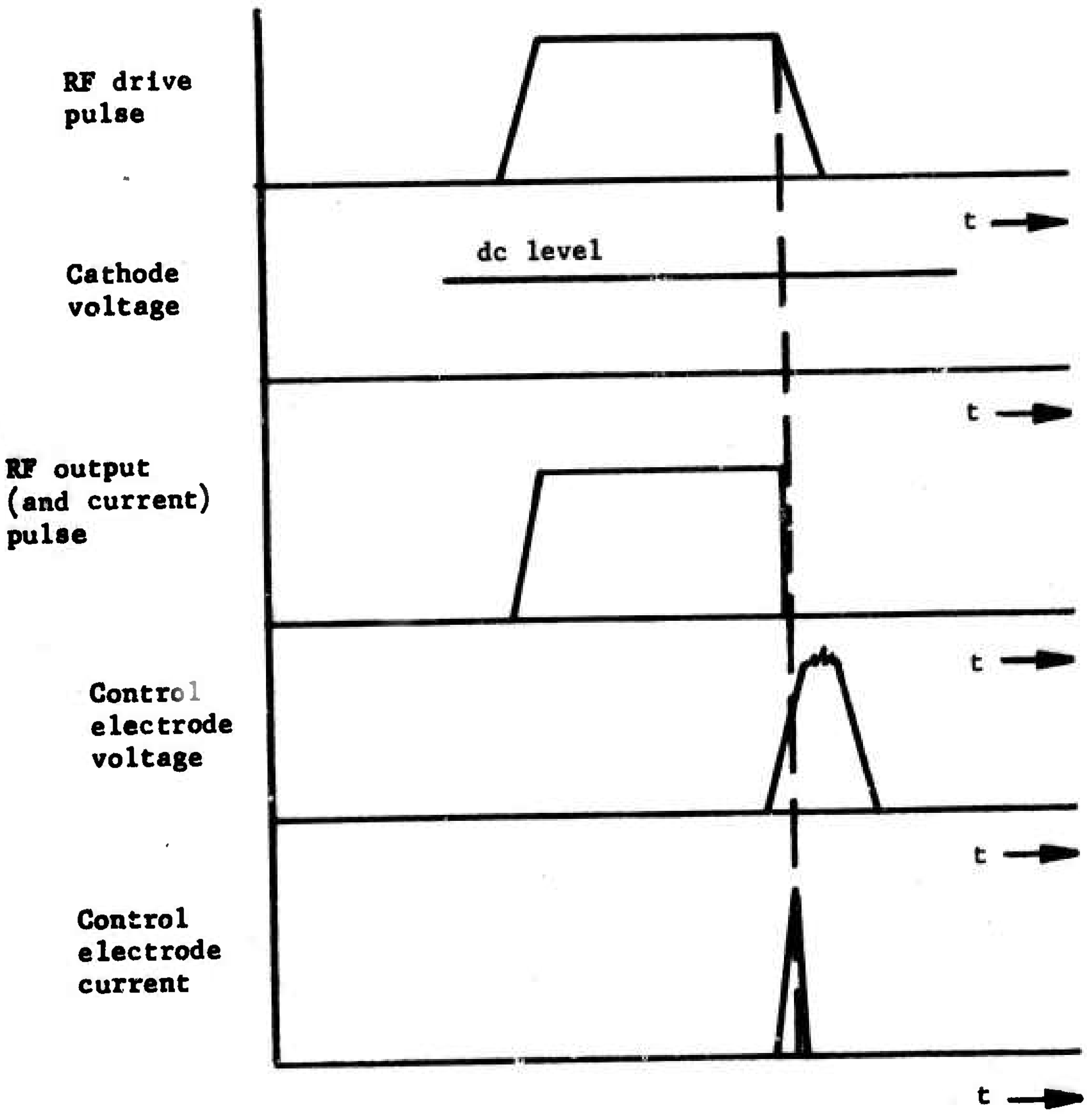


FIGURE 1 CONTROL ELECTRODE PULSING SEQUENCE

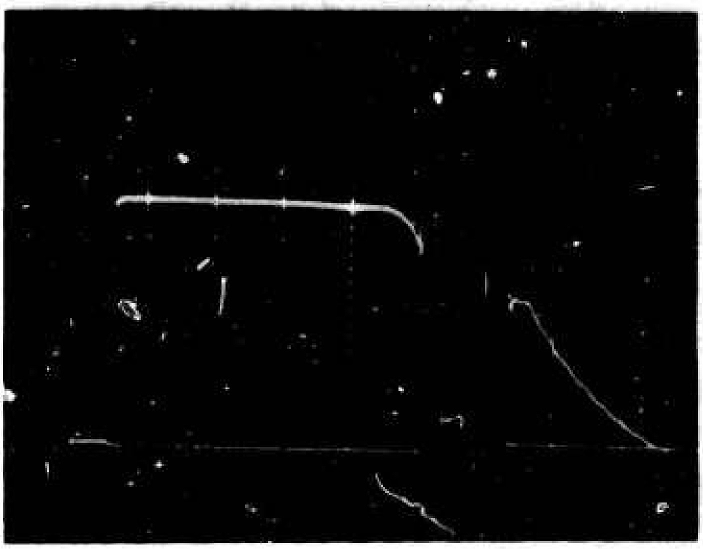


FIGURE 2 RF ENVELOPE SHOWING DELAYED CONTROL ELECTRODE OPERATION

the results of these early experiments indicated that with the application of a dc voltage to the control electrode the amplifier did turn on reliably and did turn off when the RF signal was removed. Figure 3 is a photograph of oscilloscope traces made with such an amplifier operating. A control voltage pulse is used which is sufficiently long to start before the RF drive signal and end after the RF drive signal. This was used to simulate a dc voltage on the control electrode and is shown as the upper trace. The lower trace shows a superposition of the amplified RF output and the RF drive signal. The amplifier turns itself on and off. It is felt that by further experimentation with the C-band amplifiers having variations in the location and the geometry of the control electrode and of the value of bias voltage, full performance can be achieved with self turn-on and self turn-off while still maintaining the advantages of the reentrant format.

During this reporting period, control electrodes with varying geometry were designed to be used in the SFD-237 C-band amplifier. Some preliminary experiments were performed with the present control electrode design by rotating the cathode assembly to place the control electrode partially under the RF circuits. Self turn-off has not yet been realized, but no conclusive results could be obtained other than to verify that the amplifier RF characteristics were not changed significantly by the rotation. These experiments have dealt only with a change in the location of the control electrode.

FIGURE 3 OSCILLOSCOPE TRACES FOR AMPLIFIER WITH DC VOLTAGE APPLIED TO CONTROL ELECTRODE

3.0 HIGH POWER AMPLIFIER DESIGN

The goal of this development program is to demonstrate a reentrant crossed-field amplifier capable of operating with an RF power output level of 2 Mw peak, 20 kw average over a 500 MHz band at C-band. The amplifier should be capable of operating with a 50 μsec pulse at the specified power levels. The tube is to be liquid cooled using distilled de-ionized water as the coolant for both anode and cathode. As a design objective, the amplifier is intended to provide the performance specifications listed in Table I. The program requires the delivery of an experimental tube model.

3.1 General Description of the Amplifier Design

The tube will be a forward wave, crossed-field, reentrant stream amplifier capable of operating from a dc power supply. The internal anode structure is to be a forward wave, slow wave circuit composed of a number of bars which will be coupled by a helical transmission line. The combination of bars and helix will form a non-reentrant, non-resonant RF transmission network which has its pass band between 3 GHz and 7 GHz. (The RF circuit is non-reentrant but the electron stream is reentrant.) The anode bars, which must be capable of dissipating 30 kw of power, will be cooled by passing the coolant directly through the bars. The cathode will be cylindrical and concentric with the anode and will contain an electrode which will be used to turn the amplifier off. If self turn-off experiments are successful, it is possible to include this feature in the high power experimental tube. The cathode will also be cooled by passing the coolant directly beneath its surface. The electron space charge clouds which interact with the RF wave on the anode circuit, while traveling in the same direction as the circuit wave, will be bunched during amplification but will be demodulated or debunched by passing the cloud through a drift space before the electrons emerge into the input section of the interaction space. The drift space will be relatively

free of RF fields so that debunching of the cloud will take place rapidly under the influence of the crossed electric and magnetic fields present. The drift space is also designed to isolate the RF input and RF output sections on the slow wave circuit from each other.

3.2 Design Criteria

All of the operating specifications are interdependent to some degree and design tradeoffs are necessary. In the design of this 2 Mw, 20 kw amplifier, some of the more restricting parameters are the operating voltage, the peak and average powers, and the pulse length.

The peak and average power, pulse length, and efficiency of the amplifier determine the power which is dissipated on the anode and the cathode. The operating temperature rise which this dissipation will produce depends upon the anode (or cathode) area over which it impinges and the thermal impedance between the surface of the anode and the heat sink. For the high dissipation level expected in this tube, it is necessary to make the area as large as possible and the thermal impedance as small as possible.

The physical size of the structure, and therefore the area, is governed primarily by the frequency of operation, the range of phase shift per section on the dispersion characteristic over which the amplifier operates, the operating voltage, and the number of circuit sections used in the tube. The operating frequency, of course, is not variable. The range of phase shift per section in principle is variable, but our experience with the design of these amplifiers has shown a particular range which yields the best performance and we generally restrict ourselves to that range. In practice, then, the phase shift per section is not variable. The remaining factors, operating voltage and the number of circuit sections, are the variables which we must select.

The slow wave circuit may be shown in a plan view as in Figure . It is a periodic structure made up of N elements spaced by

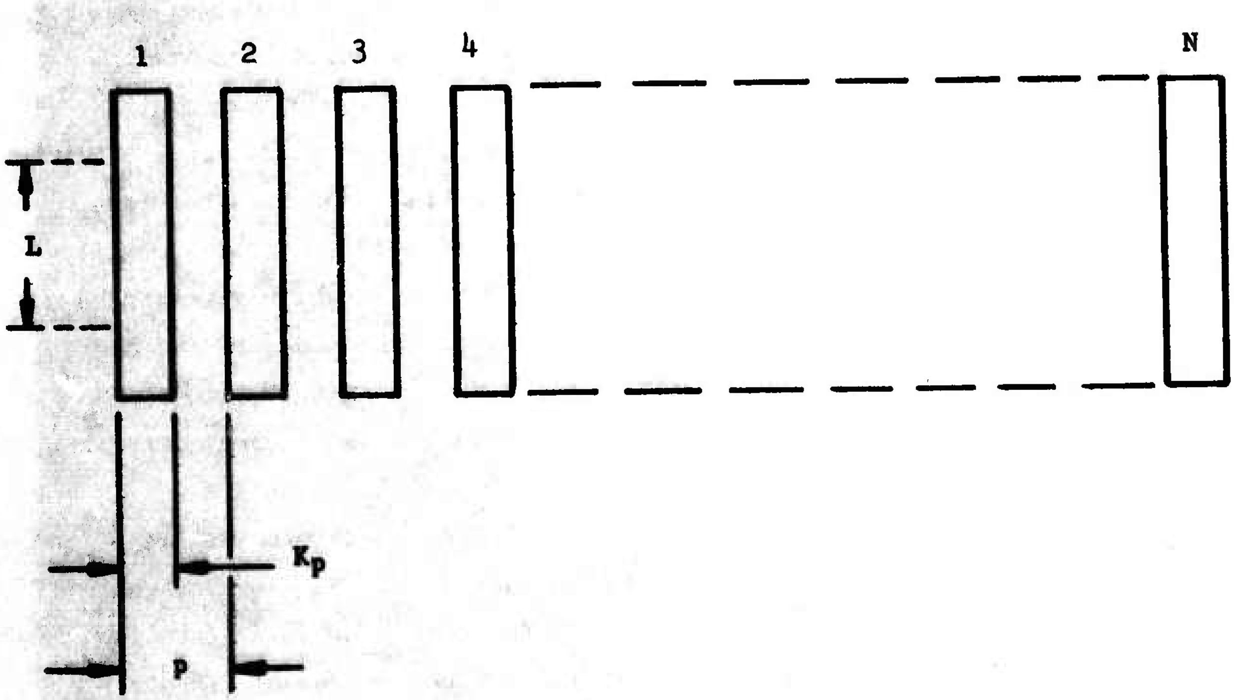


FIGURE 4 PLAN VIEW OF SLOW WAVE CIRCUIT

the pitch, p. The dissipation occurs over a length L of each element. The width of each element is some fraction K of the pitch, usually (0.5)p. The area available for dissipation therefore is

$$A = N\ L\ K\ p$$

The effect of operating voltage on the available area can be seen from the dependence of the pitch on voltage, given by

$$p = \frac{\theta\sqrt{2\eta\ V_o}}{9.16\ f}$$

where θ is the phase shift per section

η is the electronic charge to mass ratio

f is the frequency

V_o is the synchronous voltage of the slow wave circuit.

The operating voltage of the amplifier is usually 8 to 10 times V_o. To maximize the area, therefore, it is desirable to operate the tube with as high a voltage as possible.

Two limits on voltage appear in the design analysis. The first is related to the RF drive power which is available and the second to the maximum voltage gradients permissible in the structure. As the operating voltage (and the synchronous voltage of the circuit) is increased, the minimum RF drive power required for stable operation also increases. The drive power for this program will be 100 kw. From experience with slow wave circuits similar to the one we shall use (in terms of interaction impedance), operating voltages of at least 40 kv could be used without encountering RF drive power limitations. The practical limit on operating voltage will probably be the maximum permissible voltage gradient. This gradient is considerably smaller for dc operated tubes in which voltage appears on the tube continuously than it is for the pulse modulated tubes. Prior experiments to establish this maximum gradient in similar structures indicate that voltage levels up to 35 kv should be safely attainable in a design without an excessive arcing rate.

The choice of K, which will define the metal-to-space ratio (which is 1·1 for a K of 0.5) is limited to a maximum of about 0.6 in order to avoid too large a decrease in interaction impedance. The interaction impedance strongly affects efficiency, gain, and minimum RF drive power.

The choice of N is also limited by our goal of a 10 inch maximum tube diameter. The inside circumference of the slow wave circuit is given by

$$Np$$

and the circuit diameter by

$$\frac{Np}{\pi}$$

Values of N of 100 or more are practical, although the insertion loss of the slow wave circuit may be prohibitive for such a value. For high powered tubes of this general design, N is usually chosen to be between 50 and 100.

3.3 Anode Circuit Design

Based on the considerations outlined in Section 3.2, a tentative design was made in which a new slow wave circuit was used (i.e., different from that used on AF 30(602)-4082) in addition to increasing the operating voltage to 35 kv. The circuit modification was made and the operating voltage was increased to increase the thermal capability of the anode and to reduce the cathode loading. The anode circuit is generically a helix derived circuit in which the interaction height L has been extended and the thermal impedance has been reduced. More specifically, it is a helix coupled bar circuit. Some of the design parameters are shown in Table II.

3.3.1 Cold Test Results

The initial cold test results were obtained on a linear version of the anode circuit. A linear version is used at first because of the

TABLE II

PRELIMINARY ELECTRICAL DESIGN

Frequency - GHz	5.425	5.675	5.925
Phase shift per section - degrees	115	123	132
Synchronous voltage - kv	5.32	5.02	4.76
Anode-cathode transit angle - radian	2.31	2.47	2.65
Number of wavelengths	20	21	22
Characteristic magnetic field - gauss	885	862	840
Characteristic current - amps	222	203	188
Interaction impedance - ohms	38	34	31

ease of construction. The dimensions of the first linear tester are derived theoretically. Several different circuits may be needed before the proper dimensions for the operating frequency and phase shift per section are achieved. The dispersion curve for the tentative design is shown in Figure 5. The "cold" band pass of the circuit extends from approximately 3.2 GHz to 7 GHz with the hot operating band (5.425 GHz to 5.925 GHZ) placed between 115° per section and 132° per section.

3.3.2 Interaction Impedance

The interaction impedance of this circuit was measured to be 38 ohms at the lower frequency to 31 ohms at the upper frequency. The variation of interaction impedance as a function of frequency is shown in Figure 6. The variation of RF field strength across the height of the anode was also measured and is shown in Figure 7.

3.3.3 Transitional Match

The first attempts to obtain the transitional match were made by first matching to a short section of coaxial line which in turn will be matched to the standard waveguide. The first matches from circuit to coaxial line are shown in Figures 8 and 9. Figure 8 shows the input return loss and transmission through the circuit with the output terminated in a matched load. Figure 9 shows the results when the input is terminated and the output is illuminated in a matched load. The transmission loss is seen to be approximately 2 to 3 db, as was expected. At the time of this writing, the transitional match from coaxial line to waveguide was not yet attempted; however, since this is a relatively common transition, no great difficulty is anticipated.

Based upon the results obtained with the linear cold tester, a circular version which duplicates the amplifier anode has been ordered. The techniques for assembling a circular version have been worked out to provide a relatively simple construction.

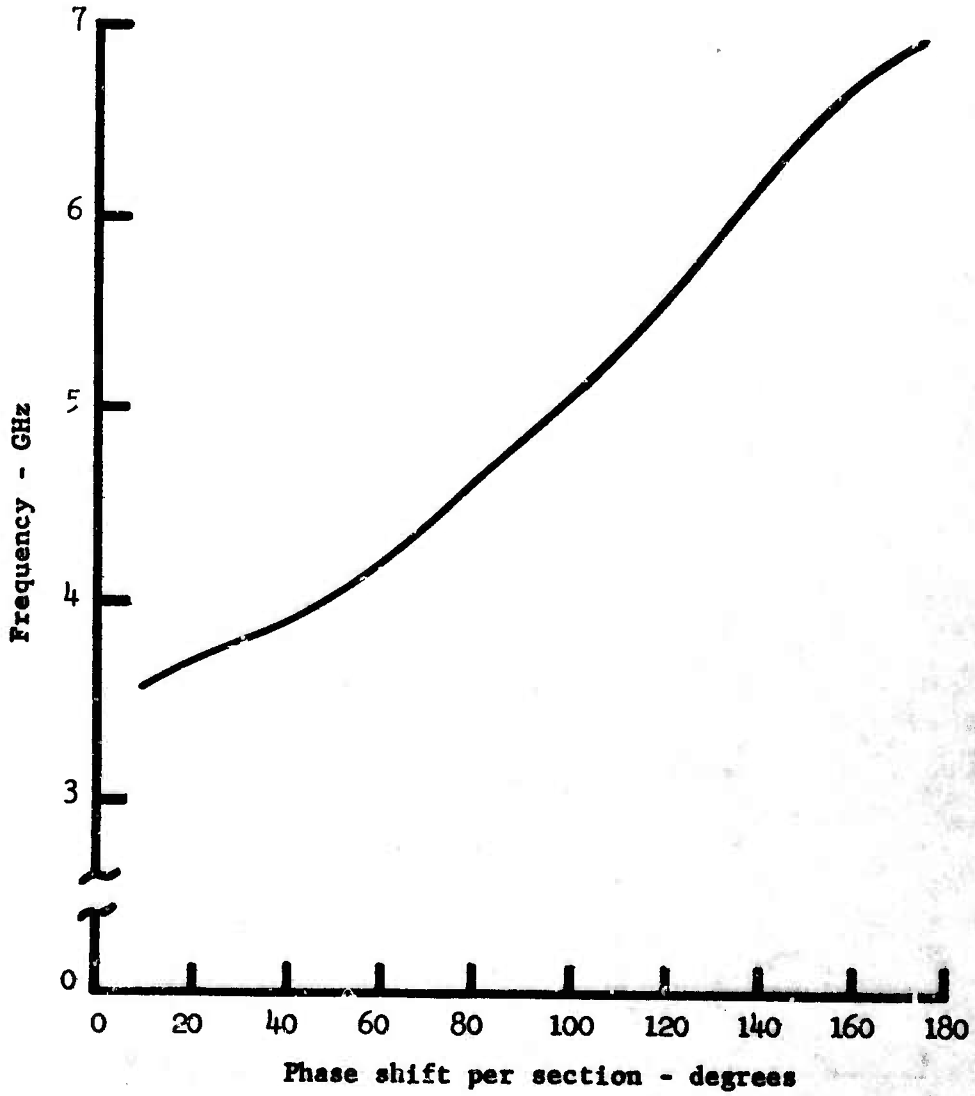


FIGURE 5 DISPERSION CURVE FOR INITIAL DESIGN CIRCUIT

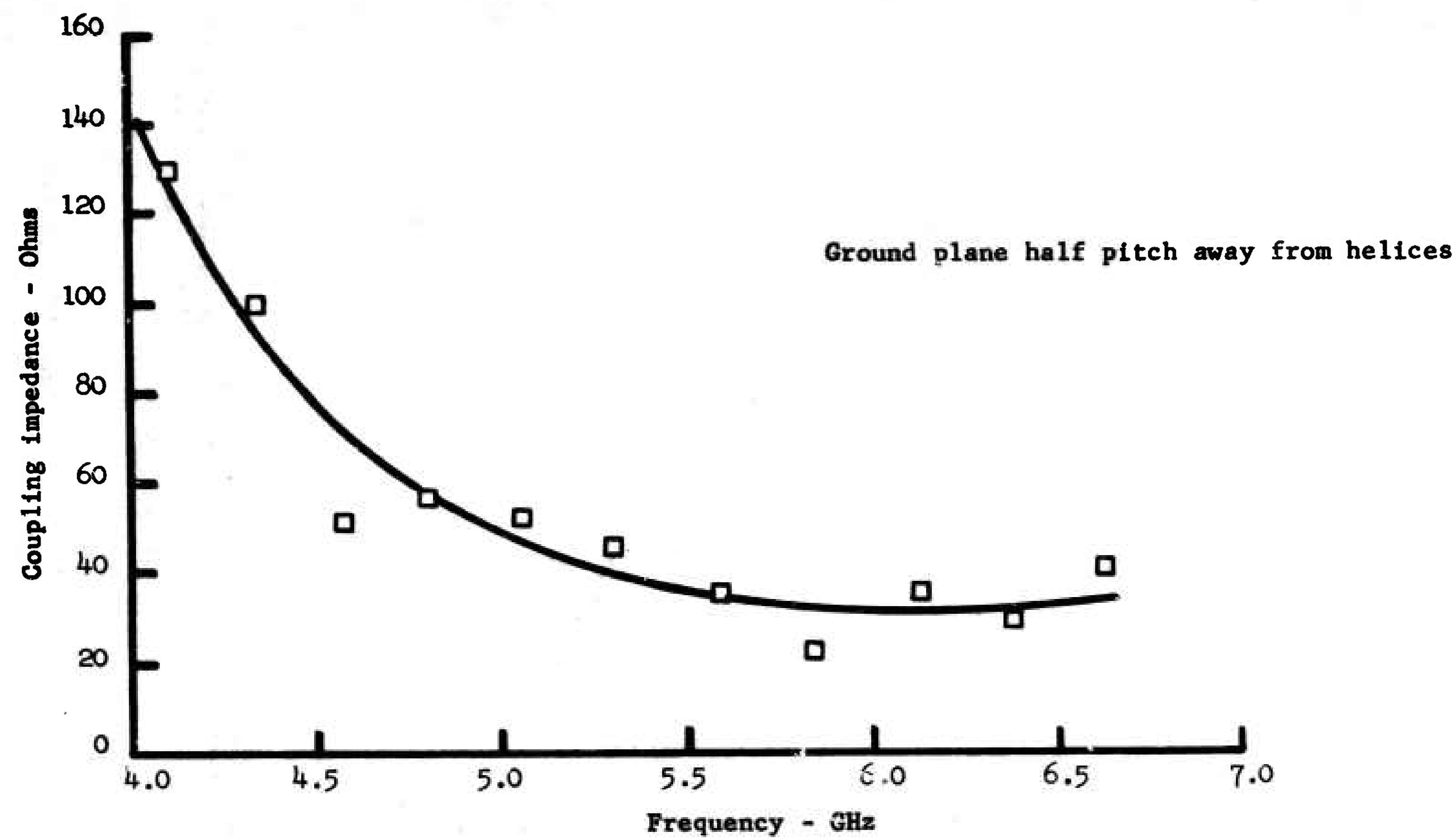


FIGURE 6 INTERACTION IMPEDANCE

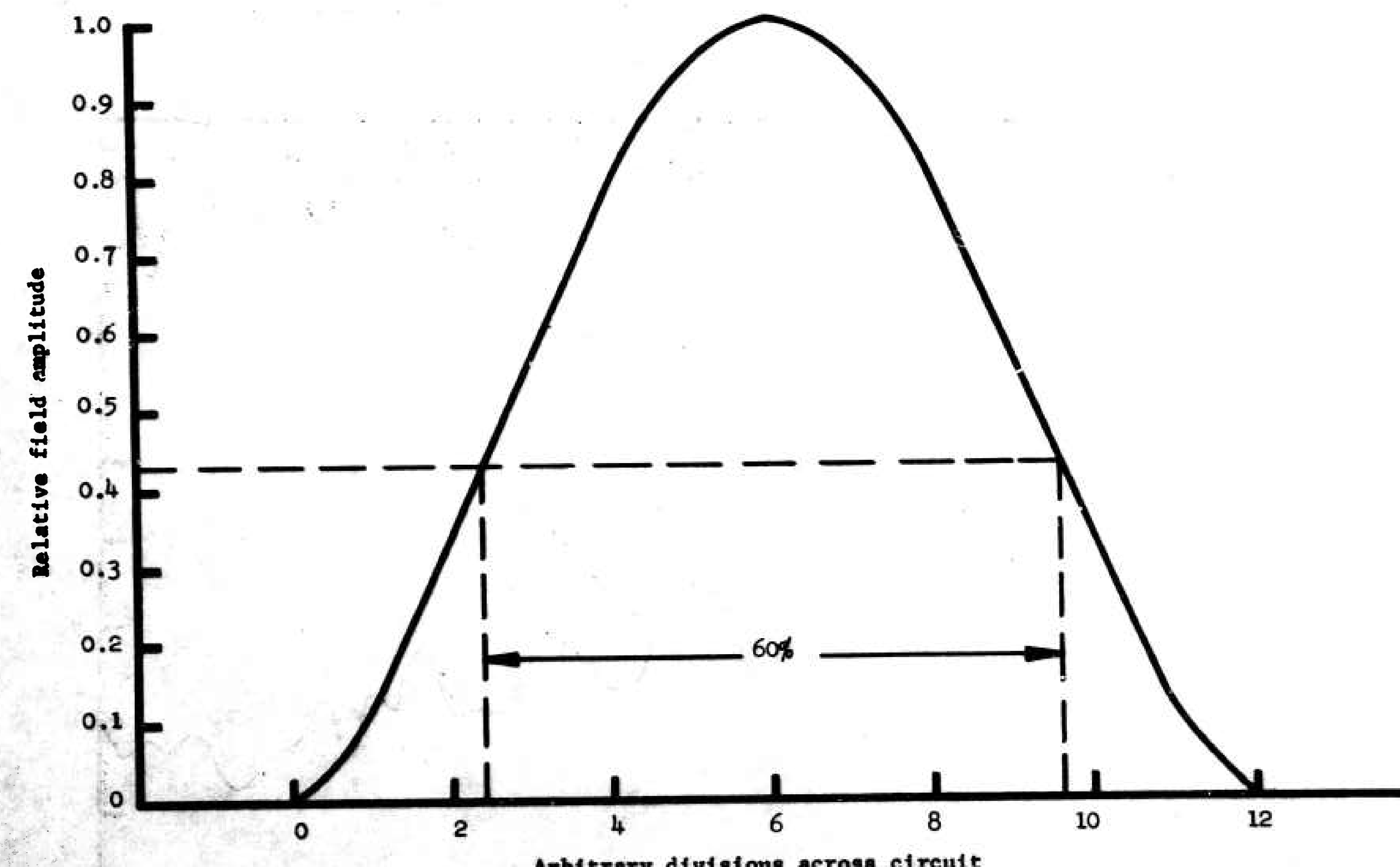


FIGURE 7 FIELD VARIATION ALONG ANODE HEIGHT

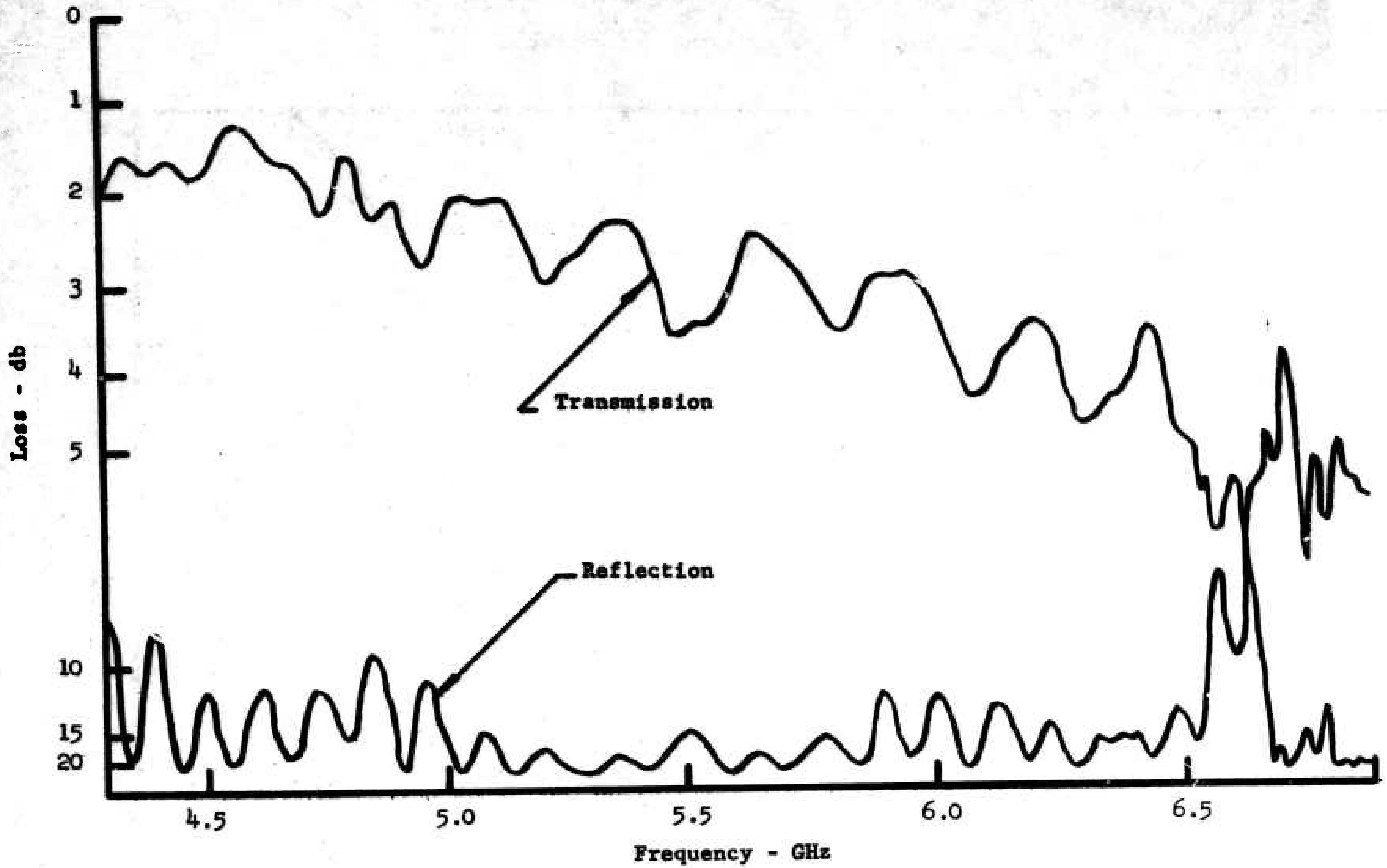


FIGURE 8 INPUT RETURN LOSS AND TRANSMISSION WITH OUTPUT TERMINATED

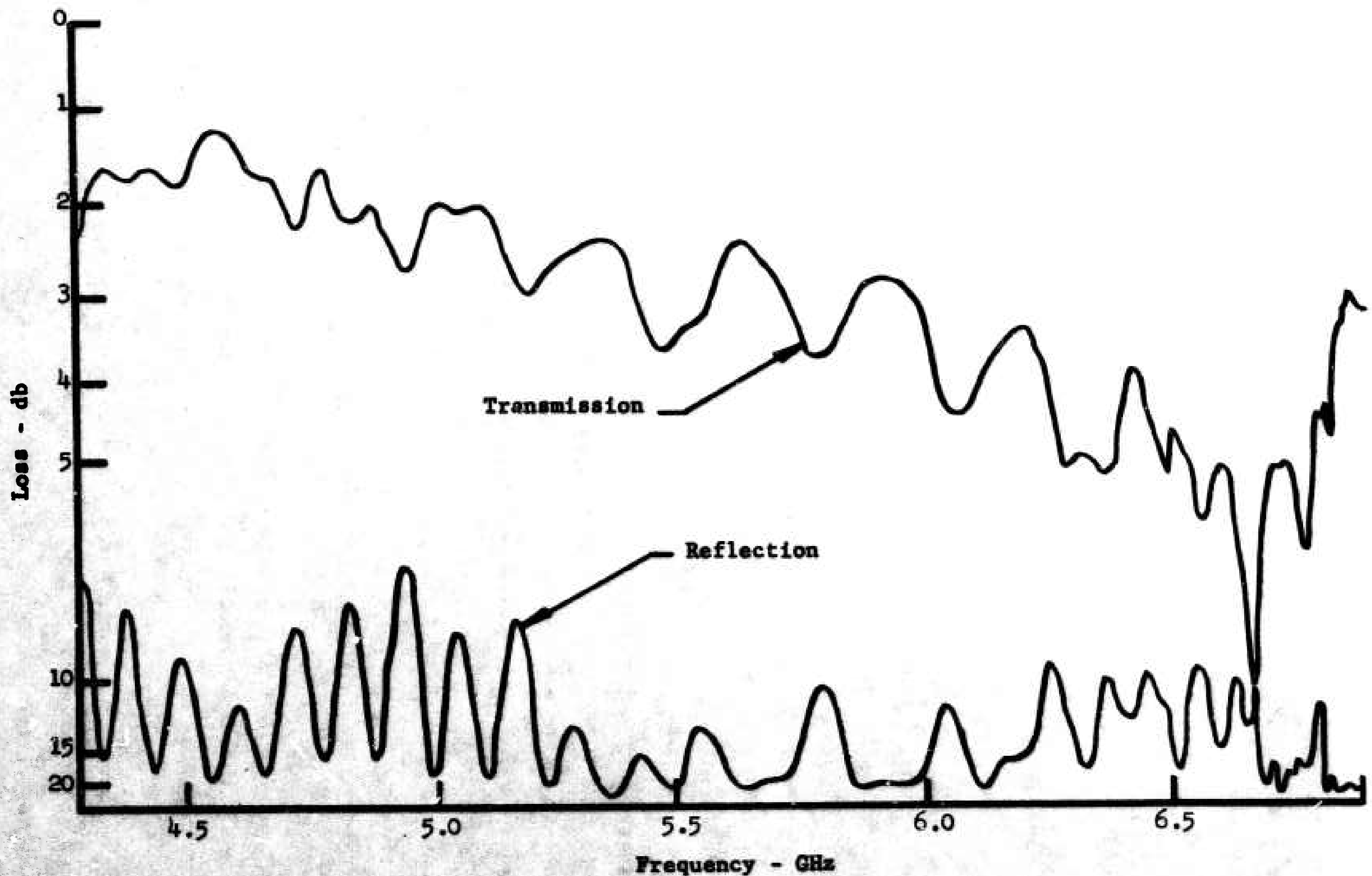
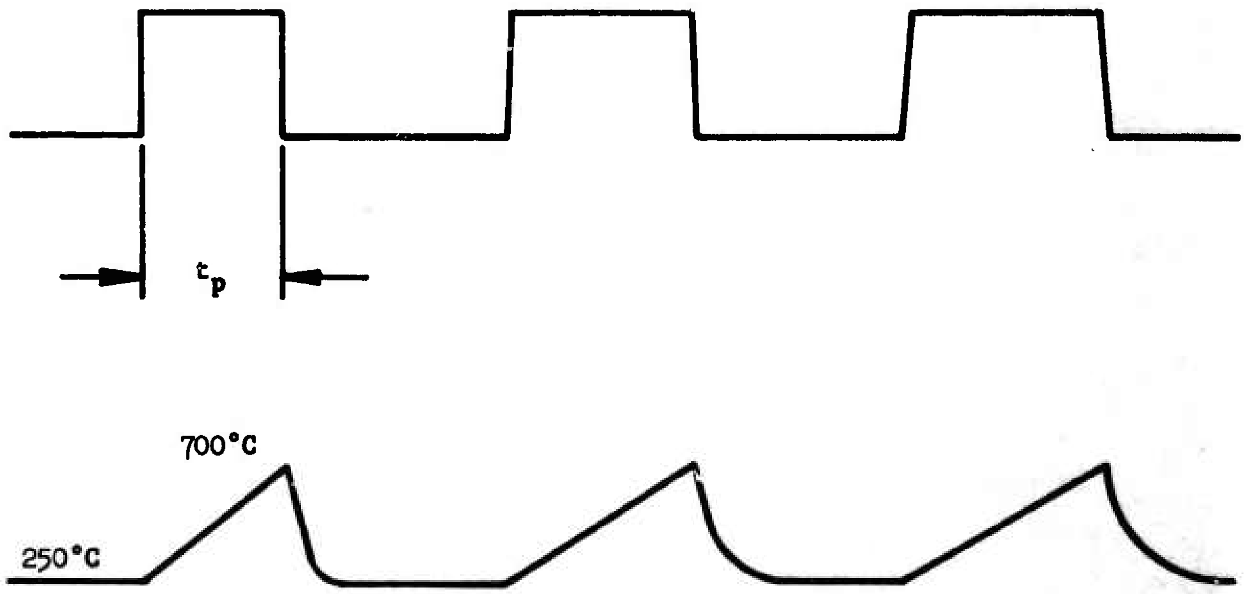


FIGURE 9 RETURN LOSS AND TRANSMISSION WITH INPUT TERMINATED

3.4 Thermal Properties

Once the circuit design was fixed, the thermal properties of the circuit were analyzed to determine the coolant requirements for the expected dissipation power. The initial calculations based on some relatively simple assumptions indicated that flow rates in the order of 0.4 gal per min per bar would be required to maintain reasonable temperatures at the vane tips near the output. The corresponding pressure drop was in the order of 75 psi. However, when measurements were made on an actual anode bar, our estimates were found to be conservative. Actual measurements indicated that the flow rate could be reduced safely to less than 0.3 gal per min per bar with a corresponding pressure drop of 42 psi. The experiment consisted of passing a controlled quantity of coolant through an anode bar while power was applied to the bar over the expected heat transfer area. The heat transfer area is that area on which the electrons will be collected. The power applied to this area was measured with a calorimeter and temperatures at various points on the bar were monitored with thermocouples. With the indicated flow rates and with the applied power approximately 10% greater than that expected in the actual amplifier, the face of the vane attained a temperature of approximately 250°C. (The temperature at the coolant-wall interface indicates that the coolant has just reached the nucleate boiling regime.) When considering operation at full power at a 50 μsec pulse length, the transient temperature rise is expected to be an additional 450°C at the end of the pulse. This results in a maximum anode vane tip temperature of approximately 700°C which is quite reasonable when a refractory metal is used on the vane tip. Figure 10 shows schematically how the vane temperature will vary during the 50 μsec pulse at full average power output.

Some experiments are planned to optimize the coolant channel geometry to reduce the coolant requirements. At this time in the preliminary design, the quantities stated above appear to be quite adequate.



t_p = 50 μsec
p_o = 2 Mw
P_o = 20 kw

FIGURE 10 VANE TIP TEMPERATURE WITH 50 μsec PULSED OPERATION

4.0 TEST EQUIPMENT

The test equipment required for the self turn-off experiments is in operating condition. The initial experiments will be conducted using pulse modulators to simulate dc operation as described in Section 2.0. The existing test set is also capable of operating a 2 Mw amplifier at 20 kw of average power so that both program objectives will at least be demonstrated on the same test set if not in a single vehicle.

5.0 PROGRAM FOR NEXT QUARTER

1. Complete construction, testing, and matching of circular cold tester.

2. Continue amplifier design and layout for the first hot tube.

3. Complete tests on first self turn-off control electrode and begin tests to evaluate geometry and position of new control electrode designs.

UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author)
SFD Laboratories, Inc
Union, New Jersey

2a. REPORT SECURITY CLASSIFICATION
Unclassified

2b. GROUP

3. REPORT TITLE
C-BAND PHASED ARRAY CROSSED-FIELD AMPLIFIER DEVELOPMENT

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)
Quarterly Report No. 1, Oct 1967-Dec 1967

5. AUTHOR(S) (First name, middle initial, last name)
Andrew Wilczek

6. REPORT DATE
December 1967

7a. TOTAL NO. OF PAGES
20

7b. NO. OF REFS
0

8a. CONTRACT OR GRANT NO.
F30602-68-C-0055

b. PROJECT NO.
ARPA Order 136

c.

d.

9a. ORIGINATOR'S REPORT NUMBER(S)

9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)
RADC-TR-68-87

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11. SUPPLEMENTARY NOTES
Project Engineer, Capt R. L. DuBois
RADC (EMATE)
Griffiss AFB NY 13440

12. SPONSORING MILITARY ACTIVITY
Advanced Research Projects Agency
Washington DC

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